2 Watershed Assessment

Planning for management and control of a watershed must begin with an understanding of the natural processes and human development characteristics that influence water flows and quality. A comprehensive assessment of watershed conditions was presented in the previous Watershed Protection Plan Update (MDC, et al., 1998) which remains as an adequate reference. Recent Environmental Quality Assessment Reports (MDC, 2002; MDC, 2003; MDC, in press) also contain useful information on natural characteristics, land use and development, hydrology, and water quality addressed at the subbasin level. A summary of this information along with any recent changes or updates are included in Section 2.

2.1 Natural Characteristics

Key Points

- The topography of the watershed is mainly hilly, encompassing flatter wetlands and flood plains, as well as some mountainous terrain with exposed bedrock.
- Watershed geology features glacial till deposits on uplands and glacial outwash deposits on lowlands and valleys.
- Soils have low to moderate erosion potential, and because the watershed is heavily forested and generally lacks steep slopes, the extent of erosion prone areas is limited.
- Soils are generally not well suited for the disposal of wastewater through septic tanks, but strict Title 5 regulations set in place in 1995 are expected to prevent newer septic tanks from posing a threat to groundwater quality and to gradually replace or upgrade older substandard tanks.
- Most of the watershed land is forested, and a large portion of the forested area is owned by the BWM or otherwise protected.
- BWM has subdivided the Wachusett Reservoir watershed into 49 smaller subbasins and uses these to organize and track watershed protection programs, identify problems, and implement solutions.

The natural characteristics of a watershed influence the hydrology and water quality of its streams, lakes and reservoirs. Natural characteristics such as subbasins, topography, geology, soils, and vegetation are considered when determining watershed protection measures

Subbasins

BWM has subdivided the Wachusett Reservoir watershed into 49 smaller subwatersheds (**see Figure 2-1**). The smaller subwatersheds are manageable units for administrating watershed protection programs, identifying problems, and implementing solutions.

Figure 2-1: Wachusett Reservoir Watershed Subbasin Delineation

Go to: www.mass.gov/dcr/waterSupply/watershed/documents/2003WachWPPfig2_1.pdf

Topography

The Wachusett Reservoir, Quabbin Reservoir, and Ware River watersheds are mainly hilly, but also encompass flatter wetlands and flood plains, as well as some mountainous terrain with exposed bedrock. The Wachusett Reservoir and Ware River watersheds have broader valleys and more wetlands compared to the Quabbin Reservoir watershed, which has narrower valleys and steeper slopes, especially on the western side, where two mountain ranges run from north to south.

Elevations in the watersheds vary from 395 feet above sea level at Wachusett Reservoir to about 2,000 feet at Wachusett Mountain (MDC, et al., 1991a-b). The watersheds include scattered areas – 14% of the Wachusett Reservoir watershed, 18% of the total watershed system – with steep slopes greater than 15%.

Geology

Most of the uplands in the watershed system are covered with glacial till deposits several feet deep. Lowlands and valleys are usually filled with stratified glacial outwash deposits of silt, sand and gravel, and occasionally with swamp deposits of muck and peat. Depth to bedrock is variable – bedrock outcrops are commonly observed on the top and sides of hills, but bedrock also tends to be found at depths of up to 100 feet (MDC, et al., 1991a-b; MDC, et al., 1998).

Soils

The predominant soils found in the Wachusett Reservoir watershed are Hinkley-Merrimack-Windsor, Paxton-Woodbridge-Canton and Chatfield-Hollis. Additional soil types are found in the upper watershed, including soils in the Peru, Marlow, Montauk, Ridgebury, and Whitman series, as well as Bucksport and Wonsqueak mucks. Many of these soils are well drained to excessively well drained, including the Hinkley-Merrimack-Windsor soils on outwash plains, and the Canton and Chatfield-Hollis soils on uplands. These soils occur on gently sloping to moderately steep areas and are very deep, except for Chatfield-Hollis soils, which typically have a depth to bedrock of only a few feet. Other soils are poorly drained, including the Paxton-Woodbridge, Peru, Marlow, Montauk, Ridgebury and Whitman soils, as well as the Bucksport and Wonsqueak mucks. The permeability of most of these soils is limited by a substratum present a few feet below the surface, except for Bucksport and Wonsqueak mucks, which are organic soils. Some of these soils occur in depressions and low flat areas in uplands and frequently contain water, including the Ridgebury, Whitman, Bucksport, and Wonsqueak soils; yet others occur in gentle to strongly sloping areas throughout the watershed, including the Paxton-Woodbridge, Peru, Marlow, and Montauk soils (MDC, et al., 1998).

Erosion Potential

The soils in the watershed system appear to have a low to moderate erosion potential. The predominant soils in the Wachusett Reservoir watershed have K factors ranging from 0.10 to 0.32 out of a possible range of 0.03 to 0.69, where higher values indicate higher erosion potential (MDC, et al., 1998). Soil erosion is only likely to be a problem in areas where slopes are greater than 15% or where vegetation has been disturbed. Because the great majority of the watersheds is forested and has slopes less than 15% (82% of the total watershed system and 86% of the Wachusett Reservoir watershed), the extent of erosion prone areas is limited.

Areas with higher erosion potential in the Wachusett Reservoir watershed are located near much of the Stillwater River; on Rowley, Ross, and Justice Hills in Sterling; and on much of the land south of Route 110 near the reservoir. Erosion has only been significant in a few locations: the area affected by the 1989 tornado, where vegetation was severely disturbed, and the steep bluffs on the east shore of the reservoir, where steep slopes coincide with thin vegetation and strong winds. Revegetation and slope protection techniques have been used in these locations to reduce erosion. No significant problems have occurred on erosion-prone areas that border tributaries (MDC, et al., 1998).

Septic Tank Suitability

According to the USDA Natural Resources Conservation Service, most soils in the Wachusett Reservoir watershed are not well suited for the disposal of wastewater through septic tanks. Many soils that are well drained to excessively well drained tend to drain effluent too quickly to effectively filter it. On the other hand, soils that are poorly drained are not well suited to contain septic tanks because they have slow permeabilities and water is usually present near the surface (MDC, et al., 1998).

The unsuitability of soils, however, can be overcome through the careful design and siting of septic systems. Septic tanks that conform with Title 5 regulations, which were significantly revised in 1995, should not present a threat to the quality of groundwater. While most septic systems in the watershed predate the 1995 Title 5 regulations, the regulations require that substandard septic systems are gradually brought into compliance through inspections at the time of sale. In addition, systems that "fail" or cause surface breakouts are required by the Boards of Health to be repaired to meet the Title 5 regulations standards. **See Section 6.1** for a detailed discussion of septic systems.

Vegetation

Vegetative cover in the watersheds consists primarily of hardwood forest (deciduous trees such as maples, birches, ashes and oaks) and hardwood forest mixed with softwood forest (evergreen trees such as pines, hemlocks and spruces) with some scattered areas of cultivated land (corn, apples, hay) and wetlands. A large portion of the forested lands in the watershed are either owned by BWM or are otherwise protected (**see Section 2.2 and Section 4**). BWM lands in the Wachusett reservoir watershed are estimated to be approximately 54% hardwood forest, 33% softwood forest, and 13% other land types, such as open fields. These lands have been actively managed for about 50 years, including thinning, cutting and planting for forest diversity and water quality (**see Section 4.2.3**).

2.2 Land Use and Development

Key Points

- The Wachusett Reservoir watershed is sparsely developed, with 70% of the land covered by forests and wetlands. Over half of these forested lands are protected, with 29% directly owned or controlled by the BWM.
- Current development remains lowest in the Quabbin Reservoir watershed and increases easterly to the Wachusett Reservoir watershed. The developed areas are primarily low-density residential, with commercial and other developed land uses less significant. Areas of higher housing density and commercial activity tend to be located near the town centers and along major roads.
- Over the next 20 years, it is expected that the majority of development will be for residential uses with the gradual conversion of some unprotected forested land into low-density residential use.

Land use and development patterns in a watershed also influence the hydrology and water quality of its streams and lakes/reservoirs, and are important considerations to determine the appropriate protection measures for the watershed. Land use and population density for the Wachusett Reservoir watershed is shown in **Table 2-1** and a land use map is presented in **Figure 2-2**.

Table 2-1
Current Land Use and Population Density
Wachusett Reservoir Watershed

Land Use (%) Excluding the Reservoir[1]							
Forest	Wetland	Agriculture	Residential	Commercial/ Industrial	Open Water	Other	Persons/ sq. mi.
63.0	6.8	7.2	8.2	0.6	8.0	6.2	253

Source: MassGIS, 1999; U.S. Census, 2002
[1] The Wachusett Reservoir surface area, when full, is 4,122 acres, which represents 5.5% of the entire watershed area.

According to 1999 information provided by MassGIS, the primary land use remains undeveloped forested land. Residential and agricultural land use is not uncommon; commercial, industrial, and other land uses (highways, waste disposal, and recreation) are less significant in the watershed. Residential land use is primarily low density, although significant areas of medium density development do exist near town centers. The commercial areas tend to be located near the town centers and along major roads. The subbasins with the most development within the Wachusett Reservoir watershed are Scarlett, West Boylston and Gates (CDM, 1998). These subbasins are located in the southeastern part of the watershed, along Gates Brook and West Boylston Brook; less than 50% of each of these subbasins remains undeveloped. In contrast, Justice Brook subbasin at the northern end of the watershed is 92% undeveloped forest, water, or wetland.

Figure 2-2: Wachusett Reservoir Watershed Land Use/Land Cover

Go to: www.mass.gov/dcr/waterSupply/watershed/documents/2003WachWPPfig2_2.pdf

Comprehensive Environmental Inc. inventoried agricultural sites for DWM in 1997. These sites included dairy/livestock farms (varying from several medium-size dairy farms to sites with two to ten animals), grazed land (pastures where livestock roam), and a variety of crop farms (orchards, truck crops, field crops, nurseries, Christmas tree farms) (CEI, 1997). The list is being field checked and updated as part of the Environmental Quality Assessment program described in Section 5.3. Agriculture is no longer considered a significant threat in the watershed due to the cumulative impact of acquisition, remediation, assistance, and farm abandonment; most remaining uses are smaller, “hobby farm” operations. **Section 6.4.2** presents a full description of agriculture in the Wachusett Reservoir watershed.

Overall, the BWM owns and/or controls about 29% of the Wachusett Reservoir watershed, exclusive of the reservoirs themselves (**see Section 4.1**). The Wachusett Reservoir surface area, when full, has a surface are of 4,122 acres, which represents 5.5% of the entire watershed area. Other state agencies, non-profit land conservation organizations, and municipalities own and protect another 14% of the watershed. Private property enrolled in the Chapter 61 tax abatement program, which helps foster private forestry, agriculture and recreation but is not a permanent form of protection, accounts for 10% of the watershed area (**see Section 4.3**). An additional 17.4% of the most sensitive areas in the Wachusett Reservoir watershed are jurisdictional under the Watershed Protection Act (WsPA); while these lands are still able to be developed, the BWM has the ability to review and minimize the impact of proposed projects located within these critical resource areas (**see Section 5.2.1**).

Table 2-2
BWM and Other Protected Open Space
Wachusett Reservoir Watershed

	Open Space as % of Watershed[1]			
Year	BWM Owned or Controlled[2]	Other Protected[3]	Total Protected	WsPA Protection[4]
2003	29%	24%	53%	17%
1998	26%	26%	52%	17%

Source: BWM GIS, 2003

[1] Watershed area excluding reservoir surface. The Wachusett Reservoir surface area, when full, is 4,122 acres, which represents 5.5% of the entire watershed area.
[2] Includes lands owned in fee, Conservation Restrictions, and land under Care and Control Agreements.
[3] Includes lands owned by other state agencies, local governments, private entities and those enrolled in the Chapter 61 program.
[4] WsPA protected areas include some acreage that is enrolled in the Chapter 61 program or is protected by private entities.

The Wachusett Reservoir watershed is mostly undeveloped, with much of the forests and wetlands either owned by the BWM or otherwise protected. Forested land which is currently not owned by the BWM or preserved by state or local governments or by private entities (approximately 26% of the Wachusett Reservoir watershed) could be developed in the future for residential, commercial, industrial or other land uses if permitted by zoning laws.

The potential for development of this unprotected land depends on many social and economic factors, including development pressure, the need or willingness of current owners to sell their land, and population growth. Information on population growth and projections is shown in **Table 2-3**.

Table 2-3
Population Growth and Projections
Wachusett Reservoir Watershed Communities

TOWN	1990 Population	2000 Population	% Change 1990 – 2000	2010 Population (Projected)
Boylston	3,517	4,008	14%	4,232
Holden	14,628	15,621	7%	16,928
Paxton	4,047	4,386	8%	4,617
Princeton	3,189	3,353	5%	3,517
Rutland	4,936	6,353	29%	7,365
Sterling	6,481	7,257	12%	7,655
W. Boylston	6,611	7,481	13%	7,749

Sources: US Census data from MA MISER, 2003; 2010 populaton projections from Central Massachusetts Regional Planning Commission and MA MISER (Sterling only), 2003.

Most of the undeveloped land is currently zoned for low density residential use (1 - 2 acre minimum lot size). Commercial- and industrial-zoned lands represent a very small proportion of the watersheds, and tend to be located near the town centers and major roads. No major development in the watersheds is expected to occur in categories such as waste disposal, recreation, or major highways. Future development in the watershed is expected to involve the gradual conversion of some unprotected forested land into low-density residential land. Recently, however, there has been a new trend in residential development. During the last few years the construction of housing intended for those people aged 55 and over has become very popular. In fact, one watershed town has seen the construction of two “over 55” housing projects and more are proposed. As the population ages, that trend is expected to continue and perhaps expand into other watershed towns.

The number of single family dwelling building permits issued over the past five years varies throughout the watershed (**see Table 2-4**). The percentage each town comprises of the watershed, as well as how much of each community is actually in the Wachusett Reservoir watershed is also presented in Table 2-4.

Table 2-4
New Single Dwelling Building Permits Issued by Town

Town	% of Watershed	% of Town in Watershed	1998	1999	2000	2001	2002	Total
Boylston	9%	56%	20	22	12	13	23	90
Holden	25%	82%	68	69	84	54	95	370
Paxton	3%	19%	19	14	17	19	18	87
Princeton	25%	82%	11	12	13	14	15	65
Rutland	8%	24%	76	71	74	70	71	362
Sterling	16%	58%	65	54	42	45	48	254
West Boylston	11%	92%	15	10	3	7	37	72

Sources: Individual Town Reports,1998 – 2002

2.3 Hydrology

Key Points

- Wachusett Reservoir is an impoundment of the Nashua River completed in 1908 as a public water supply for Boston. It measures 6.1 square miles (15.8 square kilometers) in surface area with a capacity of 66 billion gallons (250 million cubic meters) of water. Today, in conjunction with Quabbin Reservoir located approximately 25 miles to the west, Wachusett Reservoir provides water to 2.2 million residents of Greater Boston.
- Wachusett Reservoir receives more than 50% of its annual inflow from the Quabbin Reservoir. Inflows from Wachusett Reservoir's two main tributaries account for another 30% of its annual inflow.
- The elongated shape, large size and depth of Wachusett Reservoir results in long detention times, and significant dilution and settling of tributary inflows. Almost 90% of the total annual inflow to Wachusett Reservoir enters the reservoir at or above Thomas Basin, a narrow basin reservoir bounded on its lower end by the Route 12 bridge, as shown in **Figure 2-3**.
- The reservoir is subject to seasonal effects, mixing completely between the late fall and spring, and developing complete ice cover during most winters. The reservoir becomes thermally stratified in the summer as is typical of most deep temperate water bodies.
- Transfers from Quabbin Reservoir are colder and denser than Wachusett Reservoir surface water and follow a metalimnetic flow path ("Quabbin interflow") during stratified conditions that dramatically reduces the time it takes this higher quality water to reach the Cosgrove Intake (3 to 5 weeks). Transfers that are initiated prior to the development of strongly stratified conditions take longer to reach the Cosgrove Intake, but still less than would be expected from the reservoir's average residence time (6 months).
- Streamflow in the Wachusett Reservoir watershed has significant seasonal changes. Flows tend to be highest in the spring, due to snowmelt and high groundwater; and lower in the summer and early fall. Streamflow also varies in response to rainfall events, being several times higher than baseflow during storms.

The Quinapoxet and Stillwater Rivers are the major tributaries to Wachusett Reservoir accounting for 42 and 33 percent respectively of total watershed inputs exclusive of inflows from Quabbin Reservoir (**see Figures 2-3 and 2-4**). The DEP regulatory Zones A (400' around the reservoir and 100' around tributaries), Zone B (an additional half-mile around surface water reservoirs) and Zone C (the remaining watershed) are shown in Figure 2-3. Taking into account only watershed drainage and precipitation, the reservoir flushing rate is about two years. However, with the hydrologic budget enhanced by water transferred annually from Quabbin, the flushing rate of Wachusett Reservoir is reduced to approximately one year.

The Thomas Basin is an important reservoir feature that helps preserve high water quality. The basin is just upstream of the reservoir, separated from the reservoir by the Route 12 causeway. The causeway constricts the channel width from 1000 feet to approximately 50 feet. Most of the inflow to the Wachusett Reservoir (approximately 90%) passes through the Thomas Basin, including Quabbin transfers and Stillwater and Quinapoxet River inflows (**see Figure 2-3**). Under normal tributary flow conditions (non-storm and Quabbin not transferring), the residence time in the basin can be on the order of several weeks. The residence time in Thomas Basin when water is being transferred from Quabbin Reservoir is about four days, which is still a sufficient period of time to allow the settling of solids present from the tributaries. Thomas Basin is thus an effective sedimentation basin for inflowing solids and their adsorbed contaminant load (e.g., nutrients, bacteria, and possibly pathogens). While the turbidity of the inflowing streams is already low, the reduction of solids load (estimated to be 85 to 90% of entering solids) certainly contributes to the high quality of water in the main body of the reservoir (CDM, 1995).

Figure 2-3: Major Inflows to Wachusett Reservoir

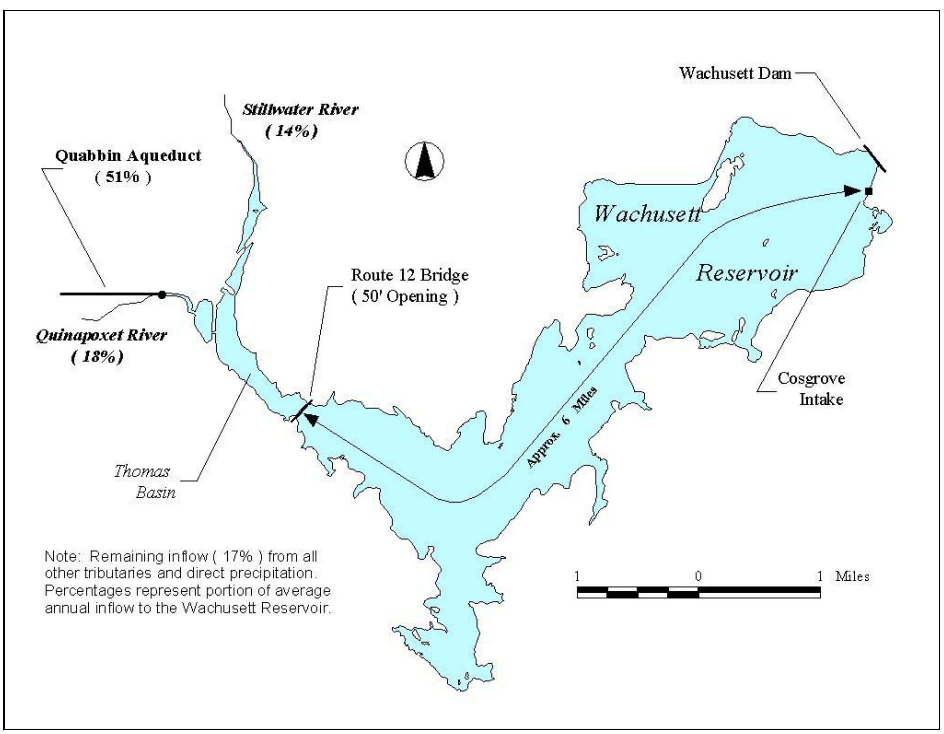


Figure 2-4: Wachusett Reservoir Watershed Hydrology and Surface Water Supply Protection Areas

Go to: www.mass.gov/dcr/waterSupply/watershed/documents/2003WachWPPfig2_4.pdf

Typical of most deep lakes and reservoirs in the temperate region, Wachusett Reservoir becomes thermally stratified in summer. As summer wanes, heat loss causes thermal gradients to weaken leading to fall "turnover" around the end of October when wind energy mixes the entire water column. Ice cover develops almost every year, usually between January and March. After ice-out, the water column undergoes another period of mixing until the onset of thermal stratification in late April.

The annual transfer of water from Quabbin to Wachusett Reservoir via the Quabbin Aqueduct has a profound influence on all functional characteristics of Wachusett Reservoir including hydrodynamics, annual hydrologic and nutrient budgets, and stratification structure. During the years 1995 through 2002, the amount of water transferred annually from Quabbin to Wachusett ranged from a volume equivalent to 44 percent of the Wachusett basin up to 94 percent. The period of peak transfer rates generally occurs from June through November. However, at any time of the year, approximately half of the water in the Wachusett basin is derived from Quabbin Reservoir.

A hydrodynamic phenomenon known as the "interflow" occurs each summer in Wachusett Reservoir as a consequence of the annual transfer of water from Quabbin Reservoir. Water withdrawn from the Quabbin hypolimnion is colder and denser relative to epilimnetic waters in Wachusett Reservoir. However, after being discharged at Shaft 1, the transfer water gains a slight amount of heat from mixing as it passes through Quinapoxet Basin and Thomas Basin and is not as cold and dense as the hypolimnion of Wachusett. Therefore, Quabbin water transferred during the period of thermal stratification flows conformably into the metalimnion of Wachusett where water temperatures and densities coincide. The term interflow describes this metalimnetic flow path for the Quabbin transfer that generally forms between depths of 7 to 15 meters in the Wachusett water column.

Quabbin interflow water quality is distinctive from ambient Wachusett water having lower specific conductivity and lower concentrations of all nutrients characteristic of Quabbin Reservoir; the interflow is conspicuous in water column profile measurements as a metalimnetic stratum of low conductivity. Profile data confirm that the interflow is a gravity-driven phenomenon spreading through the metalimnion into all portions of the basin having sufficient depth including South Bay, Andrews Harbor, west of Cemetery Island, and against the dam.

Analysis of timing and volumes required for interflow penetration based on recent transfers from Quabbin indicate that it takes about 3 to 5 weeks and from 5.5 to about 7.8 billion gallons of transfer discharge for the interflow to reach Cosgrove Intake; the rate of interflow penetration through the reservoir system depends on the timing and intensity of transfer from Quabbin.

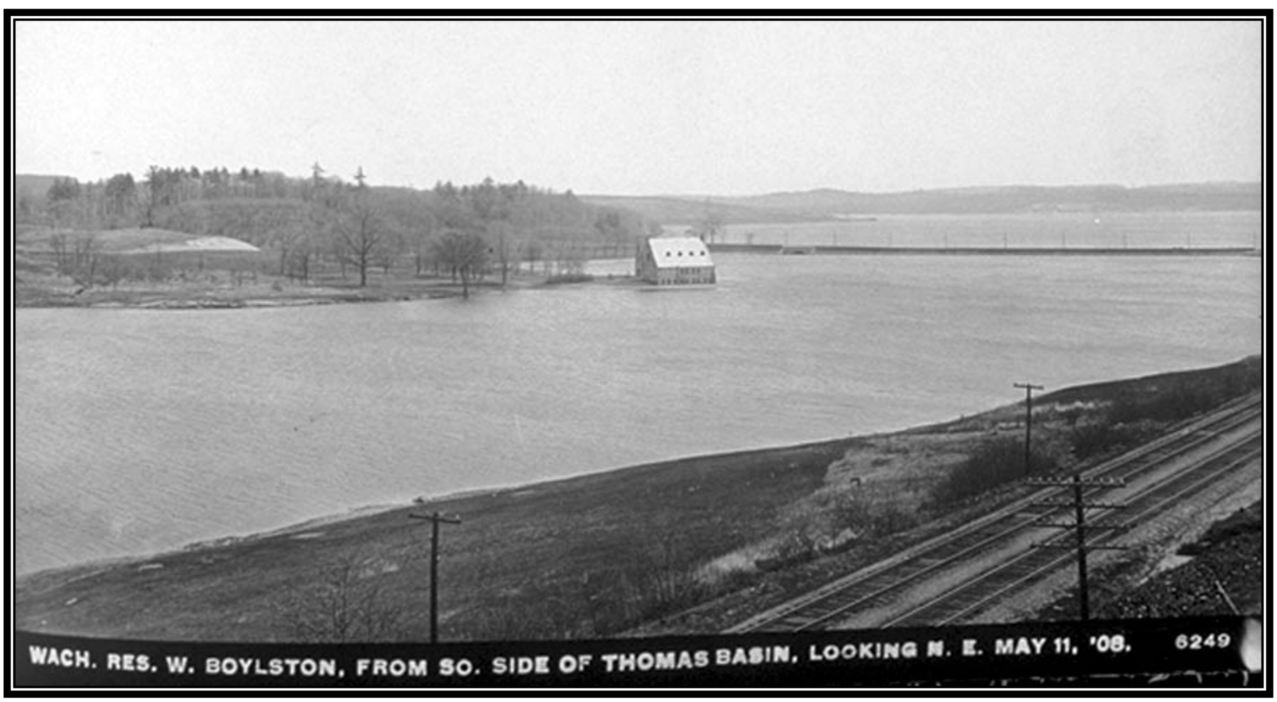
In addition to forming the interflow, Quabbin transfer water spreads out over the bottom of Quinapoxet Basin and Thomas Basin as a cold, dense underflow. Eventually this underflow displaces most of the volume in these basins except for a relatively thin surface layer of warm water derived from tributary runoff. Profile data demonstrate that this "basement" stratum of cold water can penetrate "upstream" into the upper reaches of the reservoir system as far as the railroad bridge that forms the bottleneck between Stillwater Basin and Upper Thomas Basin.

During periods of peak transfer, a remarkable manifestation of strong Quabbin underflow moving through Thomas Basin into the main basin becomes evident at the bottleneck formed by the Route

12 Bridge. The cold underflow through this bottleneck induces a counter-current of warm surface water moving from the main basin "upstream" back into Thomas Basin. Profiles recorded downgradient of the Route 12 Bridge indicate that the underflow exiting Thomas Basin becomes an interflow spreading out over colder ambient water upon reaching a location in the main basin where depths are sufficient to accommodate hypolimnetic extremes of water temperature and density (approximately 250 meters downgradient of the Route 12 Bridge).

Once established, the interflow essentially connects Quabbin inflow to Cosgrove Intake in a metalimnetic "short circuit" undergoing minimal mixing with ambient Wachusett Reservoir water. The interflow stratum exhibits a thermal gradient characteristic of its metalimnetic position and separates ambient Wachusett water composing the epilimnion and hypolimnion.

Summary information on morphology, precipitation, inflows, and outflows can be found in the previous Watershed Protection Plan Update (MDC, et al., 1998). Weekly flow data for a number of tributaries are available in the annual Water Quality Reports published by the BWM each spring (MDC, 1999c; MDC, 2000a; MDC, 2001b; MDC, 2002f; MDC, 2003). A thorough description of the "Quabbin interflow" and its impact on reservoir water quality can be found in a recently published summary of nutrient and plankton dynamics in Wachusett Reservoir (MDC, 2003a). Time-of-travel maps for baseflow and stormwater conditions were developed as part of the *Wachusett Watershed Stormwater Management Plan* (CDM, 1998).


WACH. RES. W. BOYLSTON, FROM SO. SIDE OF THOMAS BASIN, LOOKING N. E. MAY 11, '08. 6249

2.4 Water Quality

The main goal of watershed protection is to maintain a high water quality in the supply reservoirs, which depends on many watershed features, including: natural characteristics, land use and development, and hydrology. The previous sections provided an overview of these factors. This section provides a summary of the water quality in Wachusett Reservoir and the tributaries with a particular focus on fecal coliform bacteria, *Giardia* and *Cryptosporidium*, nutrients, plankton, and biomonitoring.

Key Points

Reservoirs

- A high quality and reliable source of drinking water, Wachusett Reservoir has crystalline water with low turbidity, bacterial counts, plankton densities, and nutrients.
- The reservoir has met SWTR source water quality criterion for unfiltered systems since July 1993.
- The detection of *Giardia* and *Cryptosporidium* at the reservoir intake and at Wachusett Reservoir's other sampling locations has been very low. More than 96% of total samples have been below the detection limit for *Giardia* and *Cryptosporidium* since March 1995.
- Major findings of nutrient and plankton monitoring conducted since 1998 include marked seasonal and vertical variations in nutrient concentrations mediated by phytoplankton dynamics, shifts in nutrient concentrations and the intensities of other parameters corresponding to the timing and magnitude of the annual water transfer from Quabbin Reservoir, and an annual cycle of phytoplankton succession and abundance characteristic of many temperate, oligotrophic systems.
- The macrophyte flora of Wachusett Reservoir has been characterized. The alien species posing the greatest potential threat to water quality is Eurasian Water-milfoil (Myriophyllum spicatum) and it has been the focus of intensive control efforts since 2002.

Tributaries

- Wachusett tributaries for the most part have clear water with low bacterial counts and nutrient levels. Biomonitoring of insect populations has shown that the biota present are generally indicative of healthy ecosystems and intolerant of pollution.
- Turbidity and fecal coliform bacteria in the tributaries fluctuate in response to storm flows and other conditions. Wachusett tributary fecal coliform bacteria spikes can affect the upper ends of the reservoirs, but do not impact water quality near the reservoir intake. In the Wachusett Reservoir, 90% of tributary inflows enter the reservoir at Thomas Basin, which through sedimentation and the long travel time to the intake allows bacteria to die off or disperse in surrounding waters.
- While the overall detection of *Giardia* and *Cryptosporidium* in the Wachusett Reservoir watershed was higher than at the intake, it is considered relatively low, especially because some watershed sample stations have been deliberately located in problematic rather than typical areas of the watershed. The lower pathogen incidence at the intake locations suggests that there may be attenuation of pathogen levels through in-reservoir processes such as dilution, settling, predation or die-off.
- Some tributaries in the Wachusett Reservoir watershed have elevated nitrate levels, but these tributaries are small and only contribute a minor portion of the total annual nitrate load to the reservoir. Phosphorus levels in the tributaries are very low.

There has been a significant amount of water quality data collection from Wachusett Reservoir and the tributaries. The BWM runs a comprehensive, ongoing monitoring program, which is described in Section 5. In 1995, DWM and MWRA established a regular monitoring program for pathogens, which was supplemented in 1997 with data collected to comply with EPA's Information Collection Rule (ICR). The DWM reviewed ten years of tributary water quality data (1988-1997) and published a summary report (MDC, 1999b); annual water quality reports are published as well every spring. Summaries of water quality data at the subbasin level are included in each of the three Environmental Quality Assessment Reports currently available from the BWM (MDC, 2002a; MDC, 2003; MDC, in press). Two comprehensive summary reports describing plankton populations and nutrient dynamics in the Quabbin and Wachusett Reservoirs have also been recently published (MDC, 2002d; 2003a). A general assessment of water quality is provided below; detailed information can be found in the reports listed above.

There are two regulatory requirements that relate to fecal coliform bacteria levels in Wachusett Reservoir. The SWTR requires that fecal coliform bacteria in the source water of unfiltered systems meet the following standard: at least 90% of the samples collected in the previous 6-month period must have levels less than 20 colonies per 100 mL. The Massachusetts Water Quality Standards require that fecal coliform bacteria in reservoir or tributary waters with Class A designations not exceed an arithmetic mean of 20 colonies per 100 mL, nor 10% of the samples exceed 100 colonies per100 mL.

Table 2-5 summarizes fecal coliform data collected by BWM in recent years, in terms of medians and the percentage of samples that exceed the 20 colonies per 100 mL threshold for unfiltered surface water supplies. The Wachusett Reservoir has very low median bacterial counts, and rarely exceeds the 20 colonies per 100 mL threshold. The reservoir meets the SWTR requirement for unfiltered systems, as shown in **Figure 2-5**. Although fecal coliform bacteria levels at Wachusett were higher prior to 1993, the levels have dramatically dropped due to BWM efforts and have complied with the limit since July 1993. Both the frequency and the magnitude of the exceedances of the 20 colonies per 100 mL trigger have declined. In the past, the highest coliform levels in Wachusett Reservoir, occurring in the winter, were associated with the presence of roosting gulls on the reservoir. As BWM's gull harassment program has been implemented effectively and roosting gulls were relocated, both the roosting gull population and fecal coliform bacteria levels declined. Summer concentrations of fecal coliform bacteria, historically much lower than winter levels, have also decreased.

Monitoring of tributary water quality is not required by the SWTR or other regulations. BWM conducts extensive monitoring of tributaries as a tool to identify subbasin areas requiring special attention for watershed management activities, as well as to track overall water quality and identify any trends, including improvements resulting from watershed actions. **Table 2-5** summarizes fecal coliform bacteria data in all tributaries annually over the past ten years, while **Table 2-6** summarizes fecal coliform bacteria data in each of ten tributaries during the same ten year period. In both tables an overall decline in fecal coliform bacteria concentrations in the tributaries is apparent. Both median values and the percentage of samples exceeding 20 colonies per 100 mL were lower during the past five years, and water quality appears to be improving.

Table 2-5
Fecal Coliform Bacteria Levels for Wachusett Reservoir Watershed
1993 – 2002

Year	Tributaries		Reservoir	
	Annual median	% samples > 20/100 mL	Annual median	% samples > 20/100 mL
1993	20	49%	4	17%
1994	23	53%	1	7%
1995	20	49%	3	8%
1996	24	55%	2	1%
1997	20	48%	2	5%
1998	18	47%	2	2%
1999	15	43%	1	5%
2000	12	40%	1	<1%
2001	20	50%	0	1%
2002	20	42%	1	<1%

Source: BWM Wachusett EQ Section, 2003

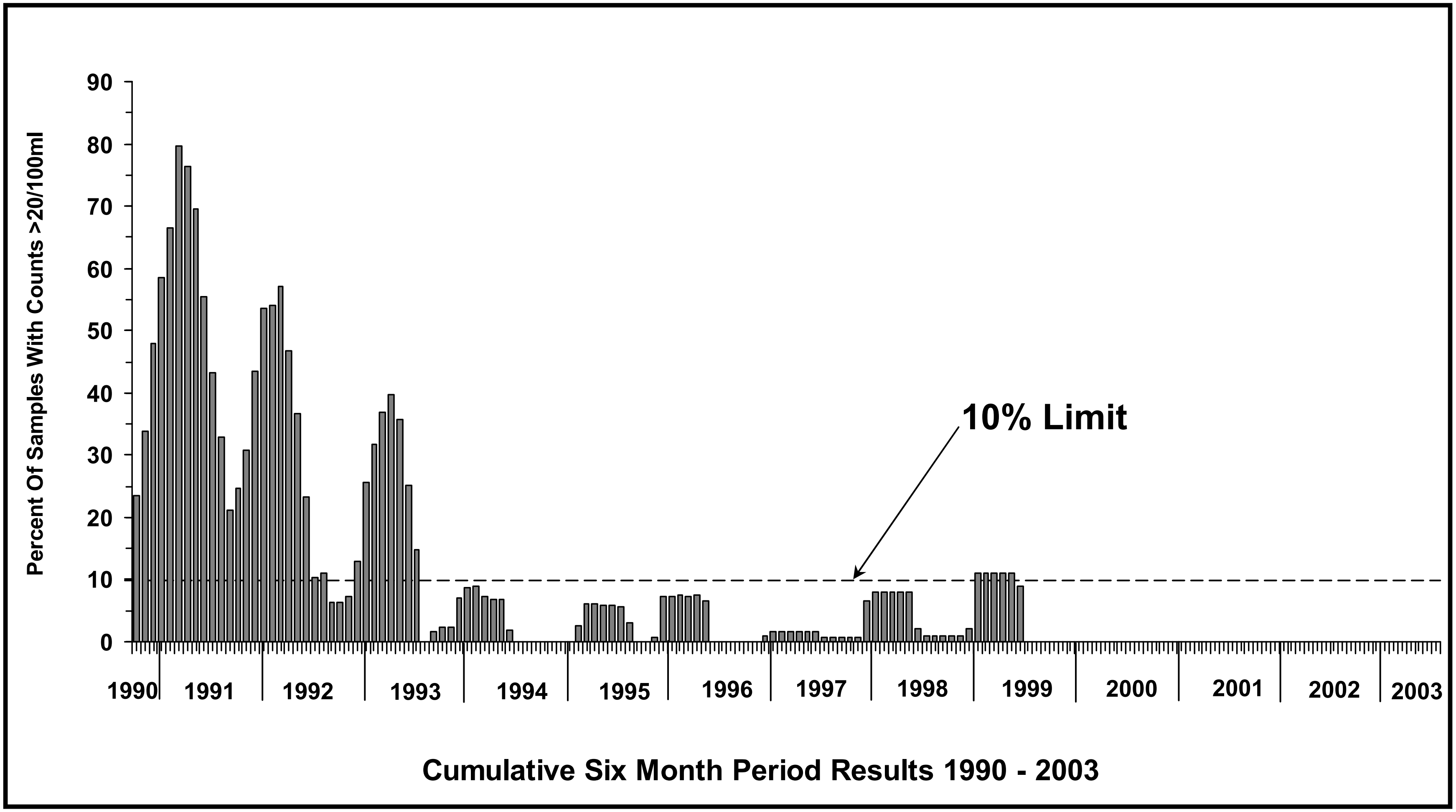
Table 2-6
BWM Wachusett Tributary Fecal coliform bacteria Data (1993-1997 and 1998-2002)

Tributary	Annual Flow into Wachusett Reservoir (%)[1]	Fecal Coliforms/100 ml			
		1993-1997		1998-200	
		Median	%>20	Median	%>20
Gates	1.3	26	59	20	45
French	0.9	17	47	10	38
Malagasco	0.5	46	56	26	51
West Boylston Br.	<0.5	72	82	40	61
Muddy Brook	<0.5	13	39	10	35
Boylston Brook	<0.5	8	33	12	38
Quinapoxet River	18	17	44	17	46
Stillwater Brook	14	30	55	20	49
Malden	0.6	22	51	20	45
Justice Brook	*	2	11	2	5

Source: BWM Wachusett EQ Section, 2003
* Tributary of Stillwater which contributes ~1-4% annual flow.
[1] Remainder of flow comes from Quabbin Reservoir.

The tributaries have relatively low fecal coliform bacteria median values, though they remain higher than the reservoir. Fecal coliform bacteria averages tend to be higher than the medians, and exceed

Figure 2-5: Fecal Coliform Bacteria Sampling Results At Wachusett Reservoir May 1990 Through July 2003 (Cosgrove Intake)



Source: BWM Wachusett EQ Section and MWRA, 2003.
NOTE: Lack of a bar on this table represents 0% of samples with counts > 20/100 ml.

the Class A standard of 20 colonies per 100 mL in most streams. Fecal coliform data exhibit a great deal of variability, especially during storm events, and concentrations can rise by several orders of magnitude. High average values and low median values suggest that the high averages are due to these occasional storm-related spikes rather than sustained elevated levels.

Biomonitoring results support this theory. To supplement other water quality monitoring efforts, BWM has conducted biomonitoring in selected tributaries to Wachusett Reservoir. Biomonitoring involves collecting samples of insects from tributary streams and comparing the community structure observed with those of “reference” stations. It provides a description of long-term cumulative conditions in the streams. For the most part, insect biota observed in Wachusett tributaries are intolerant of pollution and indicative of healthy ecosystems, comparable to biota observed at the reference stations within the watershed. Only stations on two small tributaries (Gates and Malagasco Brooks) exhibited significant impacts potentially caused by contamination during the 1990s.

More recent samples were collected during 1998 and 2001, although the 2001 samples have not yet been identified. A number of tributaries continued to have very good water quality as assessed by macroinvertebrate populations, with several showing improvements from earlier characterizations. Gates Brook sampled near the reservoir was only moderately impacted, the best assessment since 1990; an upstream station, however, remained severely impacted. Malagasco Brook also remains severely impacted and source investigation continues.

2.4.1 *Giardia* and *Cryptosporidium*

Even though testing for *Giardia* and *Cryptosporidium* is not required by EPA or the MA DEP, BWM and MWRA continues sampling for *Giardia* and *Cryptosporidium* in the watershed, reservoirs, and transmission system. Testing began on a periodic basis in 1988, using the most current methods available at the time. The test results for *Cryptosporidium* and *Giardia* are consistent with what would be expected: the highest levels found are at suspected sources upstream within tributaries of the watershed, then settling within the reservoirs, with very low levels found at the intake, and consistently low levels in the transmission system.

<u>Watershed</u>

CDM’s and MWRA/DWM’s initial testing efforts (February 1994 to June 1996) focused on familiarizing staff with sampling procedures and trying to “find” the organisms in the water sampled. For these reasons, the sites chosen were the most likely to have *Giardia* or *Cryptosporidium*, and over 20 different locations were sampled through the watersheds. Later sampling programs (July 1996 to present) focused on a smaller number of fixed stations. The Wachusett tributaries that are currently sampled are Gates Brook, a small tributary with areas of septic system problems, and French Brook, a small tributary with dense wildlife conditions. These tributaries are more representative of problematic areas rather than typical areas in the watershed. **Table 2-7** summarizes the *Giardia* and *Cryptosporidium* results for the Wachusett system since March 1995.

Source Water

MWRA's routine sampling started out with monthly samples at Cosgrove Intake and Chicopee Valley Aqueduct (CVA) Intake. Routine sampling is now weekly at the Cosgrove Intake and monthly at the CVA Intake. All samples at both intakes are currently analyzed by Erie County Water Authority laboratory, under contract to the MWRA. Each 100-liter sample is tested using the current EPA-approved ICR method. For July 1997 to August 2003, only 3 samples collected from Cosgrove Intake have been presumptive positive for the presence of *Giardia*. No samples have been confirmed positive. No samples have been presumptive or confirmed positive for *Cryptosporidium*. No samples have been presumptive or confirmed positive for *Giardia* or *Cryptosporidium* at the CVA Intake.

Table 2-7
Summary of Wachusett System Testing Results for *Cryptosporidium* and *Giardia*
(January 1998 - June 2003)

Location	# of Samples	# of Samples Below Detection Limit[2]	% Below Detection Limit	# Confirmed Samples (internal structures)	% Confirmed	# Presumed Samples (empty or amorphous oocysts)	% Presumed
Cryptosporidium							
Intake/System	256	256	100.0%	0	0.0%	0	0.0%
Watershed[1]	100	76	76.0%	1	1.0%	23	23.0%
Giardia							
Intake/System	256	252	98.4%	0	0.0%	4	1.6%
Watershed[1]	100	48	48.8%	3	3.0%	49	49.0%

Source: BWM Wachusett EQ Section, 2003

1 The data set of watershed samples include locations selected as worst-case or probable pathogen sites (Gates Brook, French Brook) and the two primary tributaries entering the reservoir (Quinapoxet River, Stillwater River).

2 Detection limits for most Intake/System samples are low, below 1.0 cysts per 100 Liters. The four presumed *Giardia* samples (empty or amorphous cysts) averaged 1.5 cysts per 100 Liters.

Transmission System

MWRA is currently engaged in a voluntary, joint research effort with Tufts University investigating levels of *Cryptosporidium* in drinking water using a new, highly sensitive test method. Since the routine, EPA-approved ICR method used by the MWRA has so few detects, no statistical comparisons were possible of human exposure to drinking water. As a result, MWRA and Tufts decided to use a more sensitive method to determine the variability, if any, of levels of *Cryptosporidium* and *Giardia*.

The research monitoring uses a weekly composite sample (some water each day for the entire week) of 1,000 liters at Shaft 9A, a site within the water system that is representative of water delivered to customers in the metropolitan Boston system. The water is filtered through an Idexx foam filter, and then analyzed. All *Cryptosporidium* oocysts, both confirmed and empty, are counted. This method, using a large sample volume and an improved filter is more than 60 times more sensitive than the current EPA-approved ICR method used by MWRA.

The data collected so far is consistent with MWRA's past data. As was expected, the much higher sample volumes and the more sensitive testing have yielded some positive samples; 20 of 124 (16%) filters analyzed between May 2001 and October 2003 were positive for *Cryptosporidium*. All but one of these positives has been below the nominal detection limit of the ICR method (1-oocyst/100 liters), and the running average is around 0.05 oocyst/100 liters.

It is important to note that *Cryptosporidium* and *Giardia* monitoring has significant limitations. The tests do not clearly distinguish between live and dead cysts, cannot determine if an organism is in fact infectious to humans, and the infectious dose of various strains of *Cryptosporidium* is not well understood. For instance, 38 of the 43 *Cryptosporidium* samples recovered were empty oocysts, had no internal structures, and most likely not viable. Tufts has also tested for *Giardia* using the same testing method as above. In 66 samples taken from July 2002 to October 2003, there has been one positive.

BWM, along with the American Water Works Association Research Foundation, is also sponsoring a UMass research study to assess watershed runoff for pathogens (**see section 8.4**).

2.4.2 Viruses and Other Pathogens

Voluntary sampling for enteric virus samples began in 1994, continued with mandatory sampling under the Information Collection Rule (ICR) from 1998-1999, and now continues with voluntary sampling.

The initial work was completed by CDM with samples from the Wachusett Reservoir and watershed, and the Quabbin Aqueduct. From 1997-1998, as part of EPA's ICR, samples were taken at Cosgrove Intake. The approved method under this program is the ICR method for total culturable viruses. This method detects the presence of many viruses that may be associated with human infection, however there are also viruses detected by this method that are not of concern to humans. While this test does not prove the presence of viruses capable of causing infection in people, it does measure the presence of a group of enteric viruses commonly found in fecally contaminated waters and EPA believes these are at least somewhat representative of human pathogenic viruses. Under the ICR program, if virus levels exceeded 100 MPN/100 L, additional monitoring would have been required. Since 1998, MWRA has voluntarily continued to test for viruses using the ICR method above. From July 1997 through August 2003, 9 of 66 samples detected viruses at low levels, with an average of 0.3 MPN/100L.

Potential sources of pathogens to Wachusett Reservoir include: tributary inflows, transfers from other watersheds, and in-reservoir sources such as birds. According to the monitoring data, tributary inflows to Wachusett Reservoir appear to be a consistent source of pathogens. While the Wachusett Reservoir Water Quality: Interim Assessment (CDM, 1995b) evaluated fecal coliform bacteria fate and transport in Wachusett Reservoir, it is unclear how far the findings apply to pathogens compared with coliforms, since pathogens require a longer time to die-off or to settle (due to smaller size and density). Monitoring data for the Wachusett system show that pathogen incidence since 1995 is lower in the intake/system than in the watershed. This difference suggests that there may be attenuation of pathogen levels through in-reservoir processes such as dilution, settling, predation or die-off. A detailed analysis to quantify the significance of attenuation due to in-reservoir processes has not been conducted.

2.4.3 Nutrients

A study of nutrient levels in Wachusett Reservoir has recently been completed (MDC, 2003a). The following conclusions were drawn; for additional details and explanation please refer to the published report.

- Results of nutrient monitoring conducted since 1998 confirm "oligotrophic" status (Wetzel, 1983) of Wachusett Reservoir based on low concentrations of total phosphorus and total inorganic nitrogen (this status is dependent on the Quabbin transfer functioning as the major hydrologic input); as an oligotrophic system Wachusett Reservoir provides high quality drinking water to consumers.

- The timing and duration of the annual transfer from Quabbin are the primary factors influencing nutrient concentrations in Wachusett Reservoir. Water quality within the reservoir basin reflects a dynamic interaction between the influence of the Wachusett Reservoir watershed and the influence of the Quabbin transfer. The Quabbin transfer is characterized by water of very low nutrient concentrations whereas the influence of the Wachusett Reservoir watershed is exerted mostly via the discharges of the Quinapoxet and Stillwater Rivers with higher nutrient concentrations. The interplay between these two influences causes the ranges of nutrient concentrations and parameter intensities to shift from one year to the next.

- Concentrations of all nutrients and patterns of seasonal fluctuation are similar across all sampling stations in the main basin of the reservoir (except for hypolimnetic values at Cosgrove Intake where mixing with the interflow caused by flow over a submerged dike obscures trends evident elsewhere). Temporary lateral gradients can become pronounced for certain parameters depending on the prevailing balance between the Quabbin transfer and watershed inputs.

- Concentrations of ammonia, nitrate, and silica exhibit marked seasonal and vertical variations due to demand by phytoplankton in the trophogenic zone (epilimnion and metalimnion) and decomposition of sedimenting phytoplankton in the tropholytic zone (hypolimnion).

- Ammonia and nitrate are depleted in the trophogenic zone in April and July respectively and remain below or near the detection limit of 5 μg/L through September, whereas concentrations of these nutrients increase in the tropholytic zone (ammonia increases in the hypolimnion from May through August and nitrate from May through fall turnover).

- Minimum concentrations of silica are measured in the trophogenic zone in July through September, whereas hypolimnetic concentrations increase from May through fall turnover.

- Concentrations of total phosphorus are low throughout the year at all stations and depths with levels generally ranging from 5 to 10 μg/L; this indicates that phosphorus is the limiting nutrient for Wachusett Reservoir phytoplankton.

- The Quabbin interflow generally forms between depths of 7 and 15 meters in the water column and its presence is evident as a metalimnetic stratum of low conductivity and also in the relatively low concentration ranges of nutrients in the metalimnion, especially nitrate, silica, and alkalinity.

- During the November through April period of water column isothermy and mixing, the water column is homogenized (no vertical gradients) with concentrations of most nutrients intermediate between summer extremes measured in the trophogenic and tropholytic zones.

- In Thomas Basin, concentrations and intensities of all parameters vary widely depending on the interplay between the Quabbin transfer and the Wachusett Reservoir watershed; during extended summer periods of transfer Thomas Basin is flushed out and essentially becomes an extension of the Quabbin hypolimnion with low nutrient concentrations, but at times when discharges from the Quinapoxet and Stillwater Rivers are the predominant loading sources (especially in spring before transfer initiation) nutrient concentrations shift to higher ranges.

- Interannual fluctuations in nutrient concentrations and parameter intensities occur throughout the main basin as a result of the divergent influences of the Quabbin transfer and the Wachusett Reservoir watershed; temporary lateral gradients across the basin can become pronounced for nitrate, silica, UV254, and conductivity either decreasing or increasing downgradient of Thomas Basin depending on the dominant influence.

Nutrient levels in the Wachusett tributaries are low as well, although considerably higher than in the reservoir. Concentrations measured from 1998 to the present are generally lower than historic values, but improved methods of analysis and lower levels of detection may have played a role in reducing average values. **Table 2-8** presents a summary of the nutrient data collected by DWM from 1998 to 2001 in the Wachusett tributaries. Average nitrate levels in the tributaries tend to be low except in West Boylston and Gates Brooks. The tributaries with high nitrate levels appear to have a minor effect on the reservoir water quality because they are small and contribute only a small portion of the annual nitrate load. Average phosphorus levels range from 0.028 mg/L to 0.063 mg/L among the Wachusett tributaries. Only Malagasco and French Brooks had an average in excess of 0.050 mg/L. **Table 2-9** presents data on nutrients in the Wachusett Reservoir.

Table 2-8
Tributary Nutrient Data Collected by BWM from 1998 to 2001

Tributary	Annual Flow %	Nitrate (mg/L)			Total Phosphorous (mg/L)		
		Minimum	Maximum	Average	Minimum	Maximum	Average
Gates	1.3	0.938	3.54	1.62	0.008	0.27	0.039
Malagasco	9.5	0.158	1.46	0.66	0.007	1.28	0.056
French	0.9	0.010	0.30	0.12	0.010	1.09	0.063
W. Boylston	<0.5	0.609	5.03	2.57	0.007	0.31	0.028
Muddy	<0.5	0.042	0.39	0.14	0.007	0.80	0.044
Quinapoxet	18	0.016	0.87	0.35	0.009	0.32	0.041
Stillwater	14	0.027	0.47	0.18	0.009	0.47	0.040
Malden	0.6	0.191	1.53	0.56	0.012	0.29	0.049

Source: BWM Wachusett EQ Section, 2003

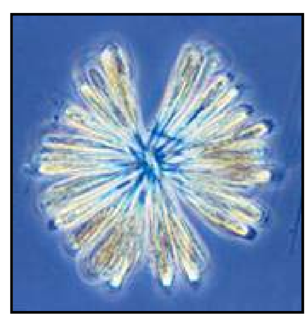
Table 2-9
Wachusett Reservoir Nutrient Concentrations
Summary of Ranges 1998-2002

Sampling Station[1]	Ammonia (NH3; µg/L)	Nitrate (NO3; µg/L)	Silica (SIO2; mg/L)	Total Phosphorus (µg/L)	UV254 (Absorbance/cm)
Basin North/3417 (E)	<5 - 12	<5 - 124	0.59 - 3.02	<5 - 13	.032 - .068
Basin North/3417 (M)	<5 - 36	<5 - 138	0.77 - 3.31	<5 - 17	.032 - .079
Basin North/3417 (H)	<5 - 41	48 - 190	1.27 - 3.92	<5 - 14	.032 - .069
Basin South/3412 (E)	<5 - 14	<5 - 172	0.56 - 3.84	<5 - 17	.031 - .085
Basin South/3412 (M)	<5 - 26	11 - 184	0.95 - 4.03	<5 - 22	.032 - .089
Basin South/3412 (H)	<5 - 44	49 - 224	1.64 - 4.13	<5 - 37	.036 - .091
Thomas Basin (E)	<5 - 18	<5 - 201	0.62 - 5.00	<5 - 23	.026- .140
Thomas Basin (M)	<5 - 18	<5 - 205	0.88 - 4.94	<5 - 22	.026 - .147
Thomas Basin (H)	<5 - 21	<5 - 236	0.92 - 4.99	<5 - 22	.027 - .150

Source: BWM Wachusett EQ Section, 2003. 1998-02 database composed of 1998-99 year of monthly sampling and subsequent quarterly sampling through December 2002, except for measurement of UV254 initiated in 2000 quarterly sampling.
[1] Water column locations key: E = epilimnion/surface; M = metalimnion/middle; H = hypolimnion/bottom.

A study of plankton dynamics in Wachusett Reservoir has recently been completed (MDC, 2003a) and the following conclusions were drawn:

- Wachusett Reservoir exhibits an annual cycle of phytoplankton succession characteristic of many temperate, oligotrophic systems consisting of the following: minimal activity in winter due to low temperatures and light intensities caused by ice cover, a spring maximum dominated by diatoms, a summer minimum following the spring depletion of nutrients, a secondary peak in the fall, and then a return to low winter densities.



Synura adamsii
(colonial chrysophyte)
Diameter of colony = 95 microns

Ceratium hirundinella
(dinoflagellate)
Total length = 280 microns

- Chrysophytes exhibit the most spatial and temporal variability among all phytoplankton taxa; they can peak asynchronously across basin and/or at different depths (generally from the surface to a depth of 8 meters); multiple years of data from Cosgrove Intake suggest that blooms of the problematic taste and odor genus Synura are inversely correlated to the relative intensity of the annual spring diatom bloom.

- Current and historical measurements of Secchi transparency are consistent with the seasonal periodicity of phytoplankton described above with greatest clarity documented during summer periods of low densities and periods of reduced transparency corresponding to spring and fall maximums.

- The zooplankton community of Wachusett Reservoir is composed of the typical freshwater fauna of rotifers (Rotatoria) and two groups of microcrustacea; Cladocera (cladocerans or water fleas) and Copepoda (copepods). Rotifers present the most diversity among Wachusett zooplankton and their populations are numerically dominant throughout the year.

Nephrocytium agardhianum
(colonial chlorophyte)
Colony length = 67 microns

Although Wachusett Reservoir experiences occasional plankton blooms of certain species that cause taste and odor problems, these blooms appear to be part of the reservoir's normal plankton successional pattern. When these plankton blooms occur, they are generally successfully controlled through the use of copper sulfate.

The macrophyte flora of Wachusett Reservoir is composed of approximately twenty species including three species alien or non-native to Massachusetts. The native Clasping-leaved Pondweed *(Potamogeton perfoliatus)* is the most widely distributed macrophyte in the reservoir system. The alien species posing the greatest potential threat to water quality is Eurasian Water-milfoil (*Myriophyllum spicatum*) and it has been the focus of intensive control efforts since 2002. Currently, this alien plant is restricted mostly to Stillwater Basin and Upper Thomas Basin.

Tabellaria flocculosa
(chain-forming diatom)
Cell length = 28 microns

Macrophyte beds are mostly located in the sub-basins composing the upper reaches of the reservoir system and in protected coves of the main basin where substrates consist of fine-grained organic substrates; Stillwater Basin supports the greatest diversity of macrophytes found anywhere in the reservoir system.

Macrophytes inhabiting Wachusett Reservoir, including alien and native species, are generally submergent in growth form; exclusively floating-leaved species such as water lilies are absent and emergent species such as sedges and rushes are restricted to the vicinity of stream inlets due to fluctuating water levels in the reservoir.